Evaluation of a Thin-Lift Nuclear Density Gauge

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This paper describes the results of a research study to determine the effectiveness of the Troxler Model 4640 thin-lift nuclear density gauge in estimating core densities. The study consisted of obtaining density measurements using cores and the nuclear gauge on seven construction projects and comparing the nuclear to core density readings. The projects were either newly constructed or under construction when the tests were performed. Correlation coefficients were determined to indicate the degree of correlation between core and nuclear densities. Linear regression was used to investigate how well the core densities could be predicted from nuclear densities. Using statistical analysis, the ranges of differences between core and nuclear measurements were established for specified confidence levels. Analysis of the data shows that the accuracy of the nuclear gauge is highly material-dependent: The gauge produced acceptable results with limestone mixtures, but it did not perform satisfactorily with mixtures containing siliceous aggregate. The data presented in this paper indicate that the gauge could be used as a quality control tool, provided calibration lines are developed for each project; calibration lines can be developed using simple linear regression.

Density is one of the most important factors affecting the performance of hot-mix asphalt concrete pavements; many highway agencies use it as a quality control parameter. In-place density has traditionally been estimated by measuring the density of cores drilled from the pavement or by using nuclear gauges. Yet the core density technique is destructive, and results are seldom available fast enough to permit effective quality control. Traditional nuclear density gauges have shortcomings that make them inaccurate for layers under 2 in. Therefore, the need is strong for a density measurement technique that can accurately and quickly measure the density of thin lifts of pavement.

The Troxler Model 4640 thin-lift nuclear density gauge was specifically designed to measure in-place density of thin pavement layers. The Texas State Department of Highways and Public Transportation, as part of its Cooperative Highway Research Program and an ongoing research project to determine density of hot-mix asphalt concrete pavements, wanted an evaluation of the Troxler 4640 gauge. The specific purpose of this study was to find out whether the gauge could accurately determine the in-place density of hot-mix asphalt concrete pavements. To this end, nuclear densities were obtained from highway sections that were under construction or were newly paved and cores were then taken from each location. The relationships between core and nuclear densities were analyzed.

EXPERIMENTAL PROGRAM

The objective of this study was to compare measured core densities with nuclear densities obtained with the Troxler 4640 gauge. Regression analyses were used to establish the relationships between the two methods, and the differences between the core and nuclear densities for each project were analyzed. The purpose of these analyses was to establish the accuracy with which the nuclear density gauge could estimate the core density.

The experimental program consisted of measuring in-place density of several highway sections during construction or shortly after construction had been completed by both methods.

TEST SITES AND METHODS

Seven construction projects at various locations throughout Texas were selected for field tests. Four projects used limestone as the primary aggregate source. The remaining three projects used siliceous aggregates.

The mixtures used in all projects were dense-graded hot-mix asphalt concrete placed on heavily trafficked roads. All projects were overlays on existing pavement surfaces; the overlay thickness ranged from 1 to 2 in.

Nuclear Density Measurements

To use the Troxler 4640 gauge, the thickness of the top layer of thin lifts of hot-mix asphalt concrete pavements must be entered in the gauge; thickness may range from 1 to 2.5 in. The gauge operates on a backsatter mode and uses an 8-mCi cesium 137 source, which emits gamma (GM) radiation, and two GM radiation detector tubes. Placing the two GM tubes at different distances from the source allows the top layer density to be mathematically determined (*1*).

According to the manufacturer, the gauge's accuracy increases as the thickness of the top layer increases, and the best accuracy is obtained with a 4-min reading time. Reading times as low as 30 sec may be used, but accuracy is lower (*2*). For this study, 1-min readings were taken. For 1-min readings, the accuracy ranges from ± 0.76 to ± 1.25 pcf, depending on the thickness of the layer (*2*).

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For each project in this study, nuclear density measurements were taken with the Troxler 4640 gauge at 15 to 25 different locations on the wheel path at intervals of 100 to 500 ft. The following briefly describes the technique used for taking the nuclear density measurement.

- A 4-min count was taken and used for each project as a baseline against which to measure other readings.
- Four 1-min nuclear density readings were taken for each core location. The gauge was rotated 90 degrees between consecutive readings. If one of the four readings significantly differed from the other three, another reading was taken without moving the gauge, when possible. Inconsistent readings appeared to occur at random and without apparent cause.
- To minimize the effects of surface voids, a very thin layer of sand was spread on the surface. Care was taken to use only as much sand as necessary. The sand passed 100 percent through the No. 40 sieve and was retained on the No. 80 sieve.
- The gauge was moved from place to place until it could be seated flat on the pavement surface. Past experience has proven that improper seating of the gauge will result in extremely low nuclear density readings.
- The gauge was approximately 50 ft from any vehicles when the readings were taken because interference from large objects could cause measurement errors.
- The thickness entered in the gauge for each location was the estimated overlay thickness.

Core Density Measurements

At each location, cores were drilled immediately after the nuclear density readings were taken. The cores were labeled and transferred to the laboratory where they were cut to the same thickness that was entered into the gauge.

All cores were dried to constant weight at room temperature before their densities were measured. Densities were measured using ASTM method D2726 (*3*).

DATA PRESENTATION

The results of the density measurements are shown in scatter plots in Figures 1 through 7. The difference between core density and nuclear measurements—the important parameter to be statistically analyzed—is shown in Figure 8 for projects containing limestone aggregate and in Figure 9 for projects containing siliceous aggregate. Figures 10 and 11 illustrate the relationship of the differences between density measurements to the density of the layer.

DATA ANALYSIS

The data graphically presented in Figures 1 through 7 indicate that there is better agreement between core and nuclear density measurements for mixtures containing limestone aggregates (Figures 1 through 4) than for mixtures containing siliceous aggregates (Figures 5 through 7). The bar graphs in Figures 8 and 9 demonstrate the same trend.

Statistical Analysis

The primary objective of this study was to determine the accuracy of the nuclear density gauge in estimating in-place density. Core density is commonly used to estimate in-place density, so the difference between core and nuclear densities was statistically analyzed. The larger the difference, the lower is the accuracy of the nuclear gauge. It should be noted, however, that there are measurement errors associated with determination of core density (see ASTM D2726 for the bias statement for core density measurement). The error in mea-

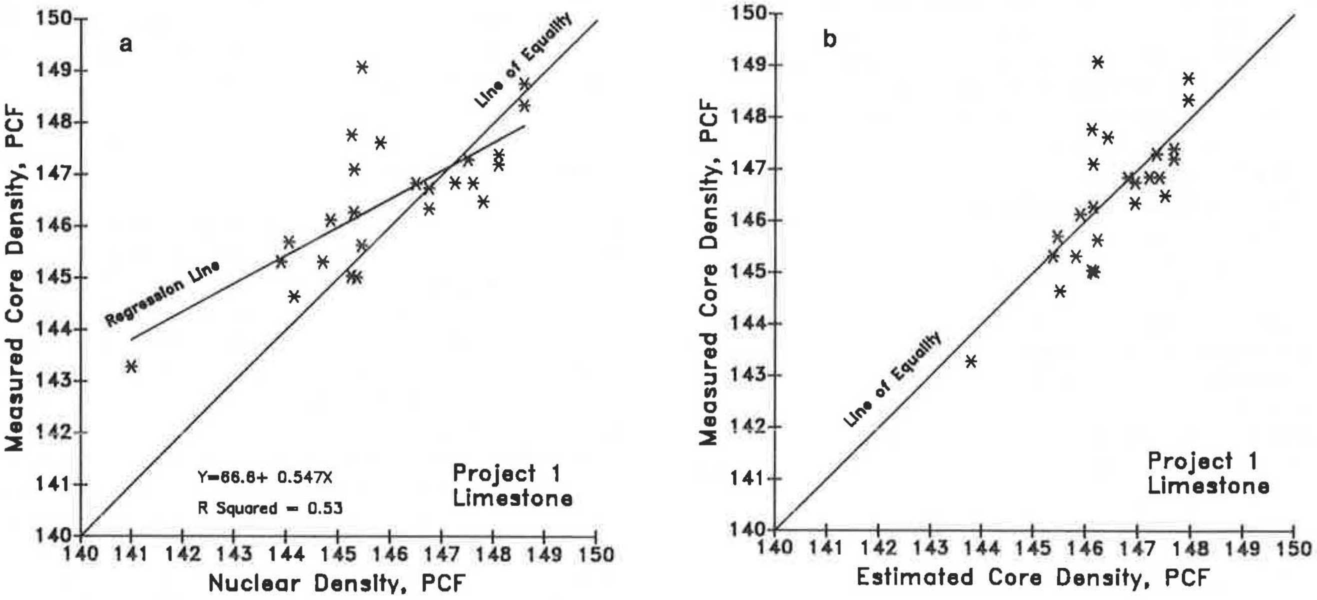

FIGURE 1 Relationship between (a) measured core and nuclear core densities and (b) measured and estimated core densities for Project 1.

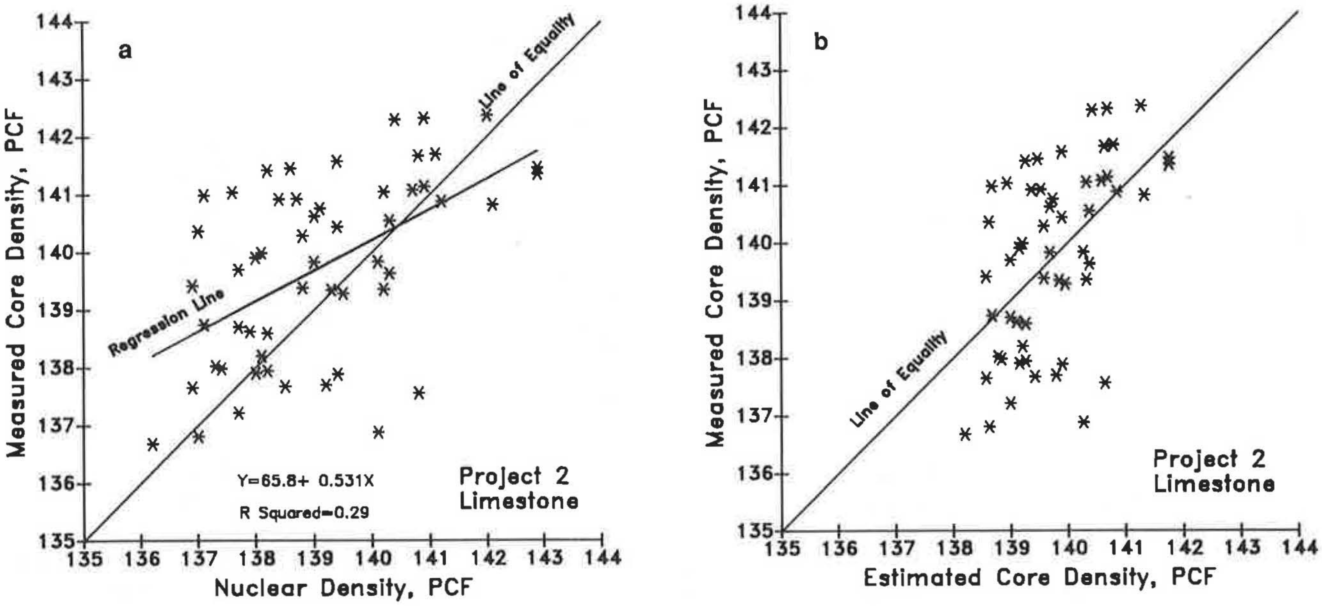

FIGURE 2 Relationship between (a) measured core and nuclear core densities and (b) measured and estimated core densities for Project 2.

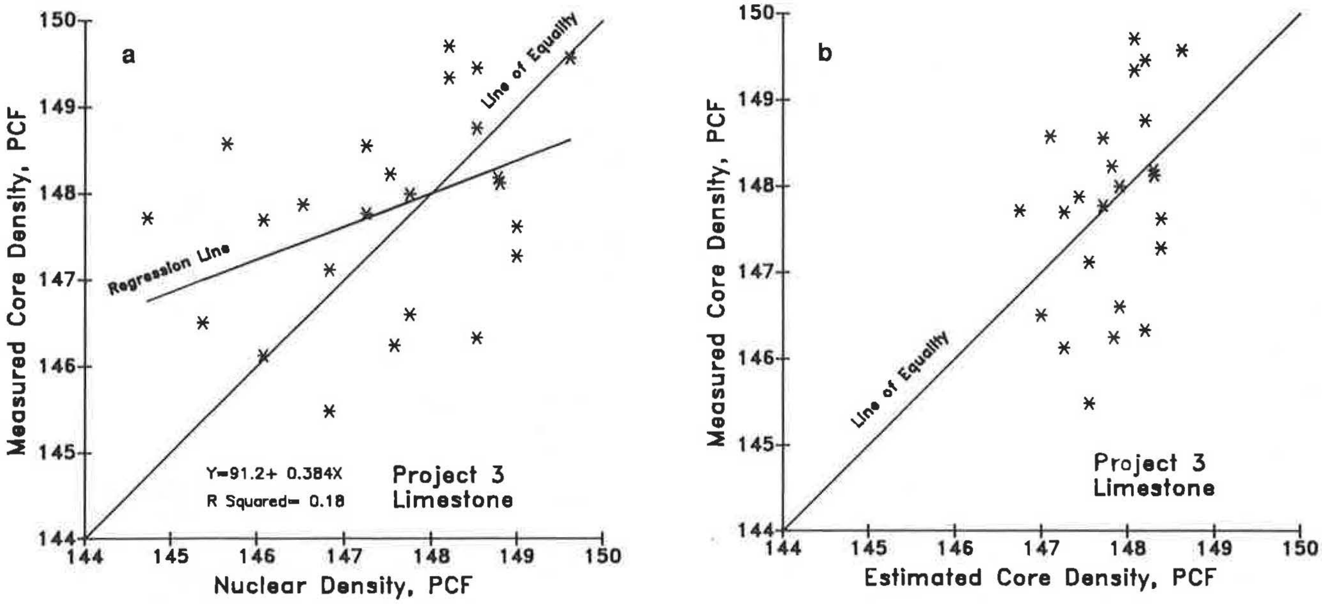

FIGURE 3 Relationship between (a) measured core and nuclear core densities and (b) measured and estimated core densities for Project 3.

surement of core density was not incorporated in the analysis because the authors intended to determine how well the nuclear density could estimate the core density, not the true pavement density.

Confidence levels and linear regression analysis were used to analyze the differences between core and nuclear densities (*4*).

Regression Analysis

A regression analysis was performed to determine how much the results could be improved if the core densities were estimated from nuclear densities based on a regression equation. Regression lines and their corresponding equations were established based on the least-square method. The relationship between the estimated core and nuclear densities is presented by $Y = aX + b$ where X and Y are nuclear and estimated core densities, respectively. The coefficients obtained from regression are a and b. Figures 1 through 7 show the values of measured core densities and estimated values of the core densities from regression as well as the difference between the two values. Scatter plots of measured core densities versus estimated core densities are given in Figures 1b through 7b.

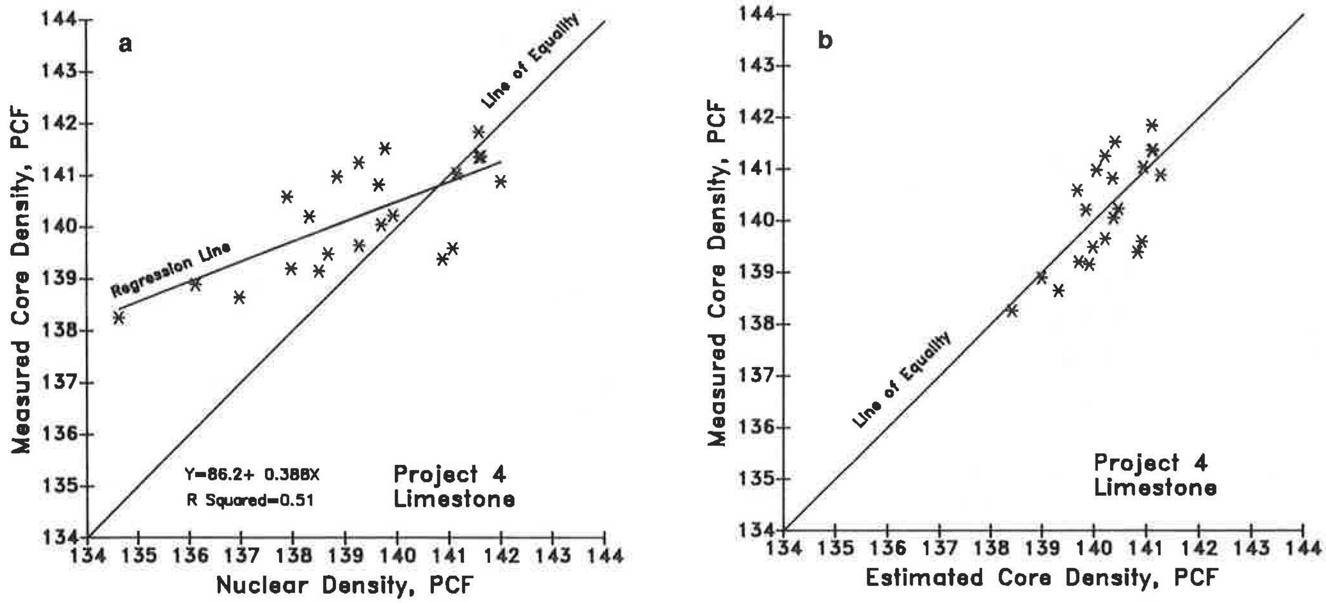

FIGURE 4 Relationship between (a) measured core and nuclear core densities and (b) measured and estimated core densities for Project 4.

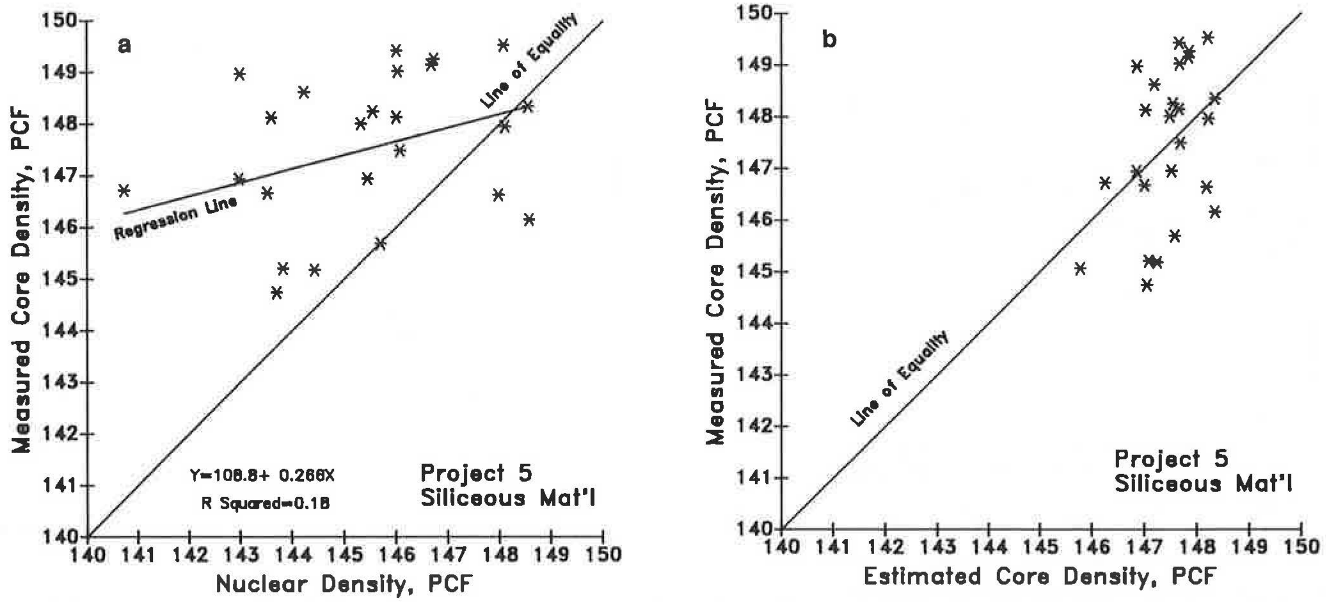

FIGURE 5 Relationship between (a) measured core and nuclear core densities and (b) measured and estimated core densities for Project 5.

Confidence Levels

Ranges of differences between core and nuclear measurements were established for certain confidence levels. The probabilities (confidence levels) used to determine these ranges were 80, 90, and 95 percent. For example, for a 95 percent confidence probability, a random nuclear measurement will fall within the established range of differences with a probability of error of 5 percent (i.e., the difference between nuclear and core densities will be beyond the range for 5 percent of the paired measurements). The *t*-distribution was used to determine the desired ranges for various confidence probabilities. (Normal distribution was not used because true population mean and standard deviation were not available, but the mean and standard deviation could be estimated based on the number of observations and existing sample size.) However, because using *t*-distribution requires that the sample be drawn from a normal population, the normality of the

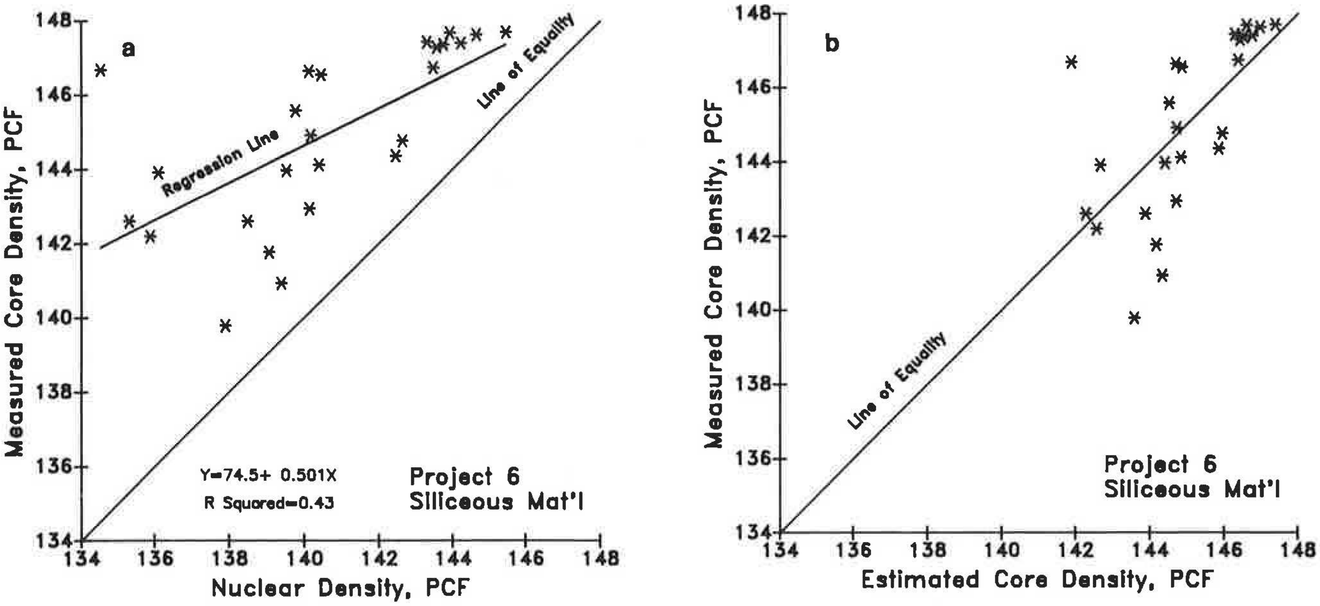

FIGURE 6 **Relationship between (a) measured core and nuclear core densities and (b) measured and estimated core densities for Project 6.**

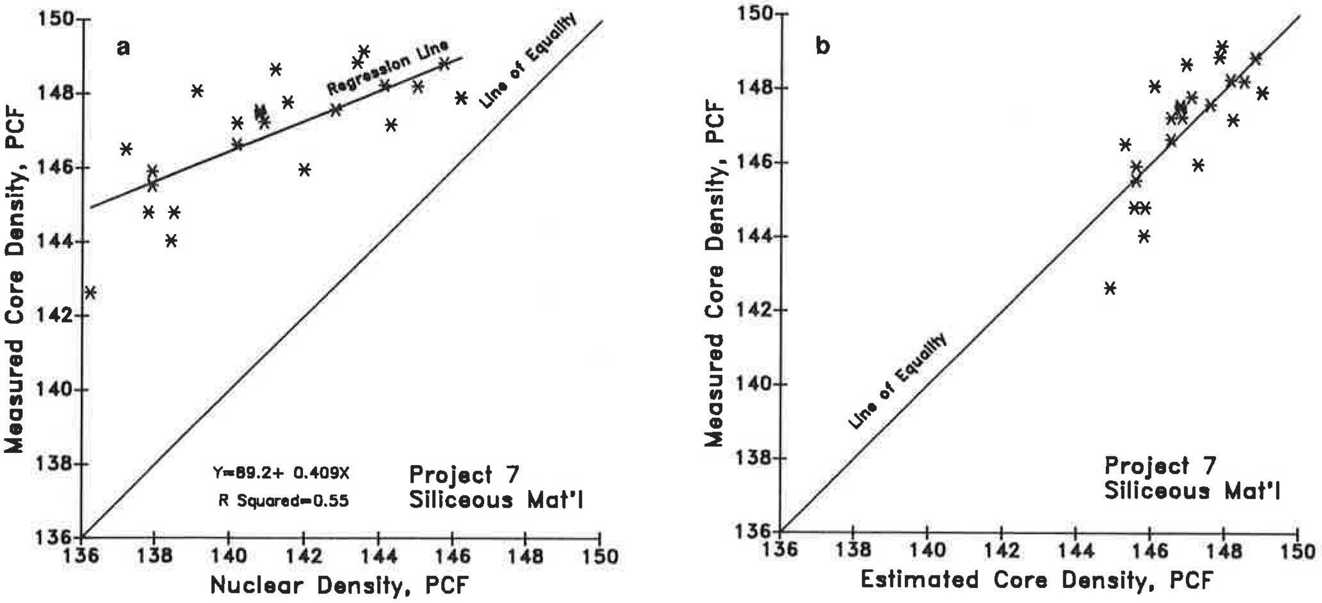

FIGURE 7 **Relationship between (a) measured core and nuclear core densities and (b) measured and estimated core densities for Project 7.**

sample data had to be checked by plotting the frequency histogram of the data. The typical histogram shown in Figure 12 does closely follow a normal distribution.

The following formulas show how the desired ranges were established:

$$d = X - Y$$

$$\bar{d} = \frac{\Sigma d}{n}$$

$$S_d = \left[\frac{\Sigma\,(d - \bar{d})^2}{n - 1}\right]^{1/2}$$

$$\nu = n - 1$$

$$R_L = \bar{d} - S_d \cdot t_\nu$$

and

$$R_U = \bar{d} + S_d \cdot t_\nu$$

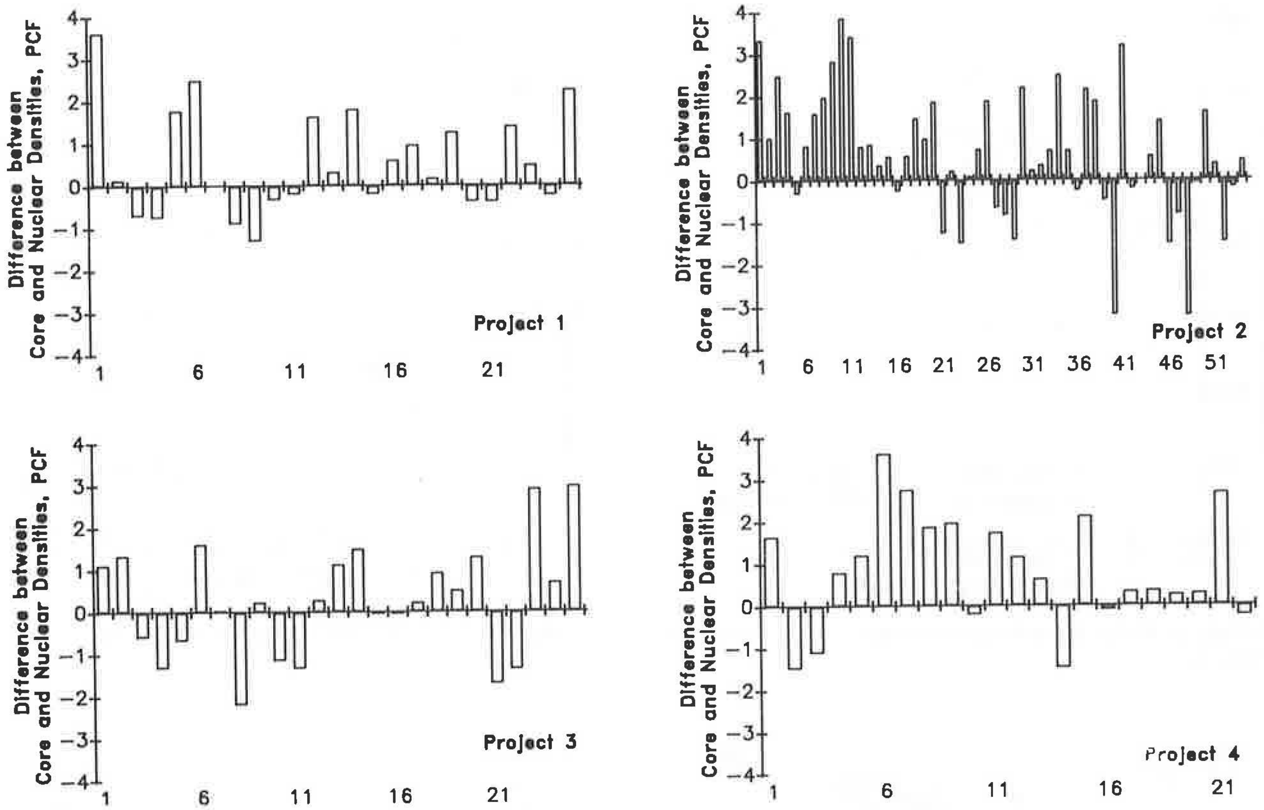

FIGURE 8 Differences between core and nuclear densities for projects containing limestone aggregate.

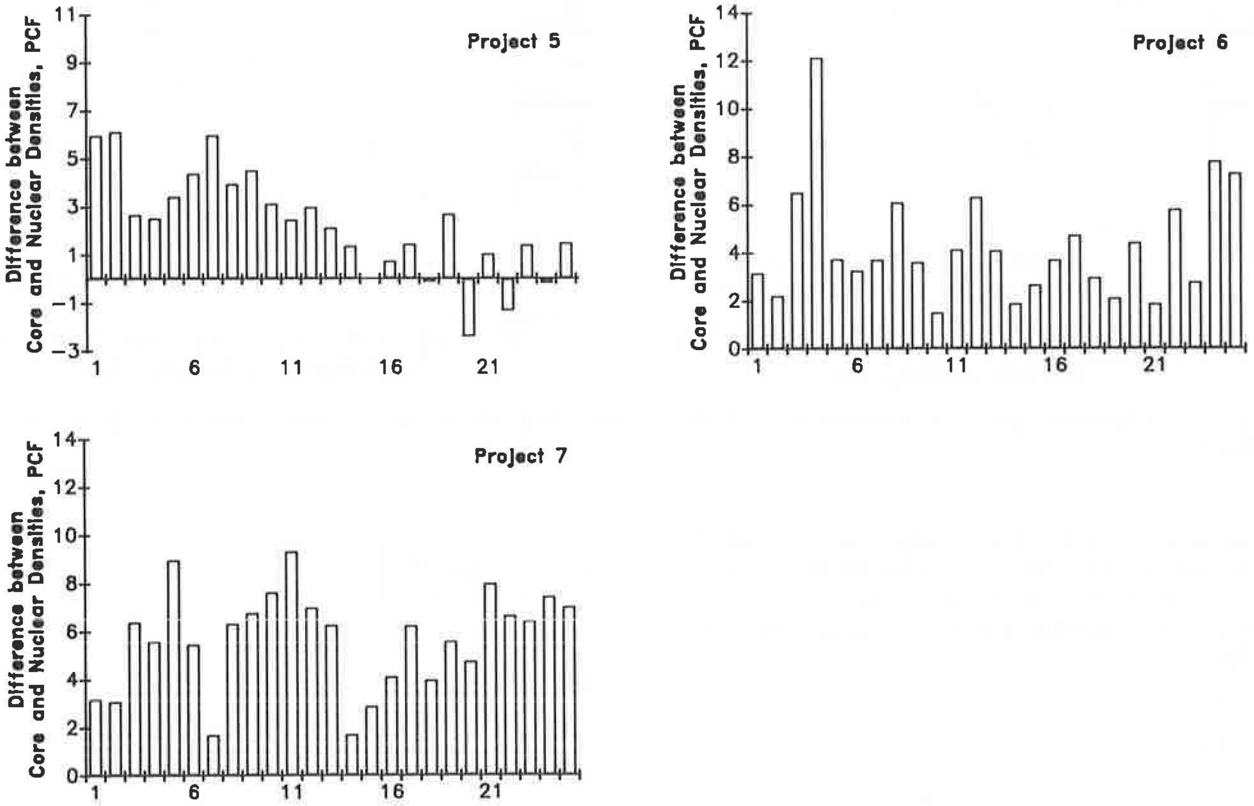

FIGURE 9 Differences between core and nuclear densities for projects containing siliceous aggregate.

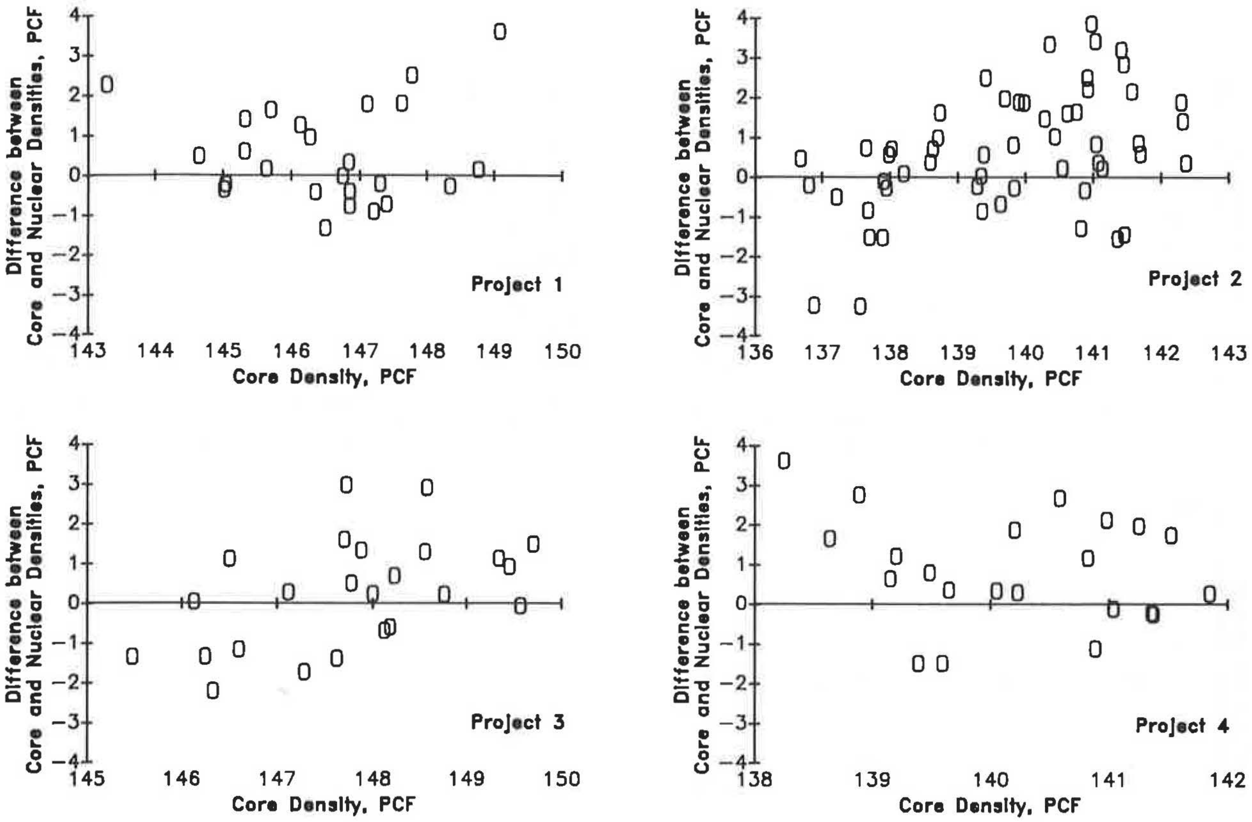

FIGURE 10 Relationship between core density and difference between core and nuclear densities for projects containing limestone aggregate.

where

X and Y = measured core and nuclear densities, respectively;
d = difference between the measurements;
$\bar{d}$ and S_d = estimates of the difference mean and standard deviation, respectively;
n and ν = sample size (number of paired observations) and degrees of freedom, respectively;
t_ν = t-value corresponding to a specified confidence probability and degree of freedom, found from t-distribution tables; and
R_L and R_U = lower and upper limits of the range of differences, respectively.

The ranges determined using t-distribution are shown in Table 1 for specified confidence levels and for different projects. The same type of analysis was performed on the data after the linear regression was applied; the results of this analysis are shown in Table 2.

DISCUSSION OF RESULTS

The scatter plots of measured core densities versus nuclear density measurements (Figures 1a through 4a) for Projects 1 through 4, which used limestone, indicate that the data are scattered on both sides of the line of equality. In some cases, the nuclear densities are higher than the core densities; in others, the opposite is true. The same trend is also evident from the bar plots in Figure 8; both negative and positive differences show up in this figure. However, for Projects 5, 6, and 7, which used siliceous material, nuclear densities tend to be consistently lower than the measured core densities (see the scatter plots in Figures 5a through 7a and bar plots in Figure 9). Moreover, the difference between core and nuclear densities is significantly higher for siliceous materials than for limestone.

The correlation coefficient for projects involving limestone varies between 0.43 and 0.73 (R squared between 0.19 and 0.53) and between 0.42 and 0.75 (R squared between 0.18 and 0.56) for those involving siliceous material. A comparison of correlation coefficients indicates that the correlation between core and nuclear densities is probably not material-dependent, whereas the nuclear density measurement itself is.

After regression equations were applied to the data to estimate core densities, the results were significantly improved. Figures 1b through 7b show that the data are considerably less scattered about the line of equality and that the differences between the measured and estimated core densities are significantly lower after applying the regression equation.

Results of the statistical analysis for confidence intervals are presented in Table 1. The table shows that, for Project 1, there is a 95 percent chance that the difference between the core and nuclear density measurements will not exceed 3

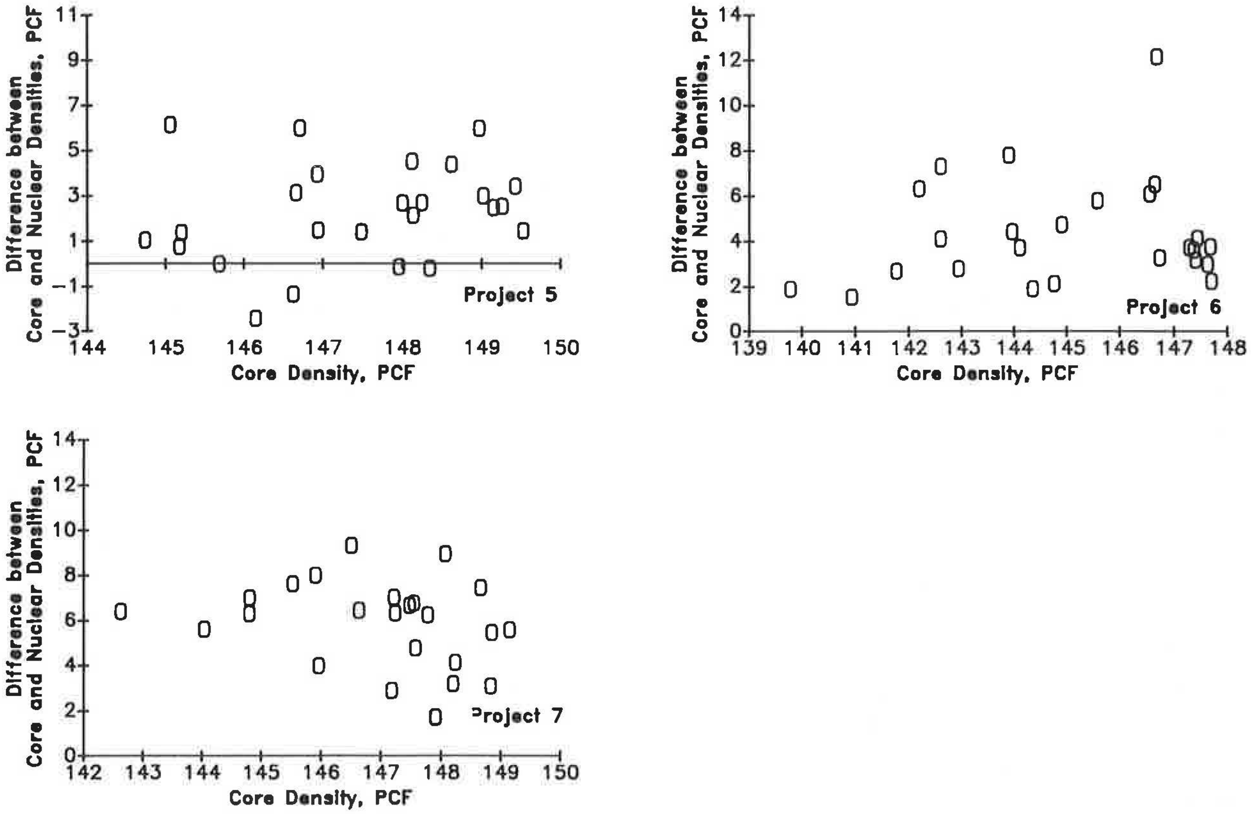

FIGURE 11 Relationship between core density and difference between core and nuclear densities for projects containing siliceous aggregate.

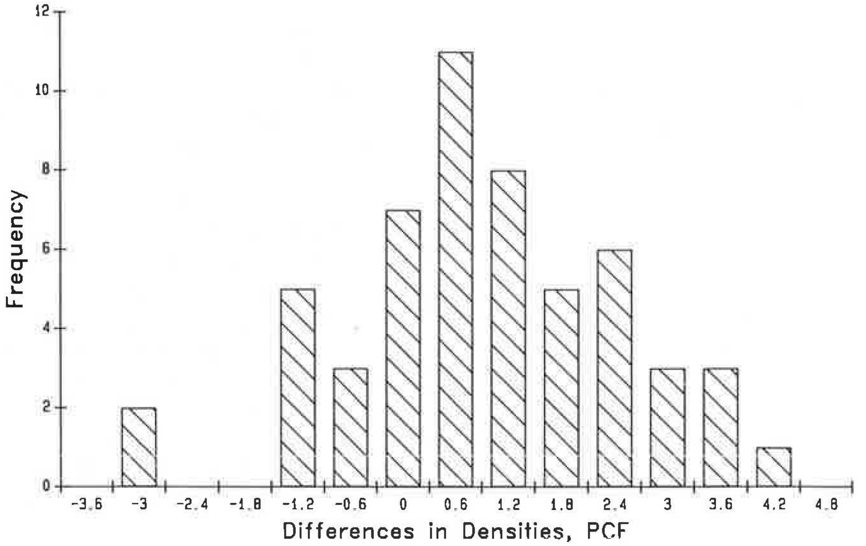

FIGURE 12 Typical histogram of the difference between core and nuclear densities, Project 2.

TABLE 1 RANGE OF DIFFERENCES BETWEEN MEASURED CORE DENSITY AND NUCLEAR DENSITY FOR VARIOUS CONFIDENCE INTERVALS BEFORE APPLYING REGRESSION ANALYSIS

PROJECT	COUNT	MEAN OF DIFF. (PCF)	STAND. DEV. (PCF)	STAD. DEV. OF MEAN	CONFID. LEVEL (%)	t-VALUE	LOWER LIMIT (PCF)	UPPER LIMIT (PCF)
1	25	0.5	1.2	0.240	80	1.318	-1.08	2.08
1	25	0.5	1.2	0.240	90	1.711	-1.55	2.55
1	25	0.5	1.2	0.240	95	2.064	-1.98	2.98
2	54	0.6	1.5	0.204	80	1.298	-1.35	2.55
2	54	0.6	1.5	0.204	90	1.674	-1.91	3.11
2	54	0.6	1.5	0.204	95	2.006	-2.41	3.61
3	25	0.3	1.33	0.266	80	1.318	-1.45	2.05
3	25	0.3	1.33	0.266	90	1.711	-1.98	2.58
3	25	0.3	1.33	0.266	95	2.064	-2.45	3.05
4	22	0.9	1.34	0.286	80	1.323	-0.87	2.67
4	22	0.9	1.34	0.286	90	1.721	-1.41	3.21
4	22	0.9	1.34	0.286	95	2.080	-1.89	3.69
5	25	2.3	2.16	0.432	80	1.318	-0.55	5.15
5	25	2.3	2.16	0.432	90	1.711	-1.40	6.00
5	25	2.3	2.16	0.432	95	2.064	-2.16	6.76
6	25	4.3	2.3	0.460	80	1.318	1.27	7.33
6	25	4.3	2.3	0.460	90	1.711	0.36	8.24
6	25	4.3	2.3	0.460	95	2.064	-0.45	9.05
7	25	5.7	2.02	0.404	80	1.318	3.04	8.36
7	25	5.7	2.02	0.404	90	1.711	2.24	9.16
7	25	5.7	2.02	0.404	95	2.064	1.53	9.87

pcf. Similar conclusions can be drawn for other confidence probabilities and other projects. This table also shows clearly that the results are better for projects involving limestone material than for those involving siliceous material.

The results of a similar type of analysis after applying regression are shown in Table 2. The ranges of differences before and after regression are compared in Figure 13, which shows confidence intervals for all projects at 95 percent probability. Obviously, regression equations can significantly improve the nuclear density results.

Therefore, it seems possible to establish an appropriate regression line based on a reasonable number of core and nuclear density measurements and to use that line to estimate core densities from nuclear measurements. However, the degree to which a regression line will improve the estimate is not well established. Moreover, analyses indicate that the accuracy of the Troxler 4640 nuclear density gauge depends on the mixture which is being measured.

SPECIAL CALIBRATION

Troxler Electronics has suggested a calibration method for the 4640 thin-lift density gauge. The procedure requires obtaining 5 cores from the roadway for a density estimate and 20 nuclear density readings for reestablishing density parameters for each project. The procedure is based on the fact that nuclear density readings are influenced by three parameters, A, B, and C, as used in the following equation:

$$D = (1/B) \times \ln[A/(CR + C)]$$

where

D = nuclear density,
CR = count ratio,
A and C = parameters that depend on gauge geometry, and
B = parameter that depends on material property.

TABLE 2 RANGE OF DIFFERENCES BETWEEN MEASURED CORE DENSITY AND NUCLEAR DENSITY FOR VARIOUS CONFIDENCE INTERVALS AFTER APPLYING REGRESSION ANALYSIS

PROJECT	COUNT	MEAN OF DIFF. (PCF)	STAND. DEV. (PCF)	STAD. DEV. OF MEAN	CONFID. LEVEL (%)	t-VALUE	LOWER LIMIT (PCF)	UPPER LIMIT (PCF)
1	25	0.0	0.9	0.180	80	1.318	-1.19	1.19
1	25	0.0	0.9	0.180	90	1.711	-1.54	1.54
1	25	0.0	0.9	0.180	95	2.064	-1.86	1.86
2	54	0.0	1.3	0.177	80	1.298	-1.69	1.69
2	54	0.0	1.3	0.177	90	1.674	-2.18	2.18
2	54	0.0	1.3	0.177	95	2.006	-2.61	2.61
3	25	0.0	1.06	0.212	80	1.318	-1.40	1.40
3	25	0.0	1.06	0.212	90	1.711	-1.81	1.81
3	25	0.0	1.06	0.212	95	2.064	-2.19	2.19
4	22	0.0	0.71	0.151	80	1.323	-0.94	0.94
4	22	0.0	0.71	0.151	90	1.721	-1.22	1.22
4	22	0.0	0.71	0.151	95	2.080	-1.48	1.48
5	25	0.0	1.33	0.266	80	1.318	-1.75	1.75
5	25	0.0	1.33	0.266	90	1.711	-2.28	2.28
5	25	0.0	1.33	0.266	95	2.064	-2.75	2.75
6	25	0.0	1.8	0.360	80	1.318	-2.37	2.37
6	25	0.0	1.8	0.360	90	1.711	-3.08	3.08
6	25	0.0	1.8	0.360	95	2.064	-3.72	3.72
7	25	0.0	2.02	0.404	80	1.318	-2.66	2.66
7	25	0.0	2.02	0.404	90	1.711	-3.46	3.46
7	25	0.0	2.02	0.404	95	2.064	-4.17	4.17

Based on the manufacturer's information, *A*, *B*, and *C* can be established for each project by using the recommended calibration technique, but that technique needs to be tried in the field to test its validity.

CONCLUSIONS

Based on research for this study, it appears that the accuracy of the Troxler 4640 thin-lift nuclear density gauge varies from project to project and depends on the materials involved. Better accuracy was observed for mixtures containing limestone than for mixtures containing siliceous aggregates.

The gauge proved to be very sensitive to improper seating; it must therefore be used by experienced and knowledgeable personnel to minimize measurement errors. The use of calibration lines through regression analyses significantly improved the prediction of core densities from nuclear measurements. However, even with calibration lines, the gauge's results must be treated cautiously: an acceptable range of difference between core and nuclear density measurements must be clearly specified, as well as an acceptable risk of error.

ACKNOWLEDGMENT

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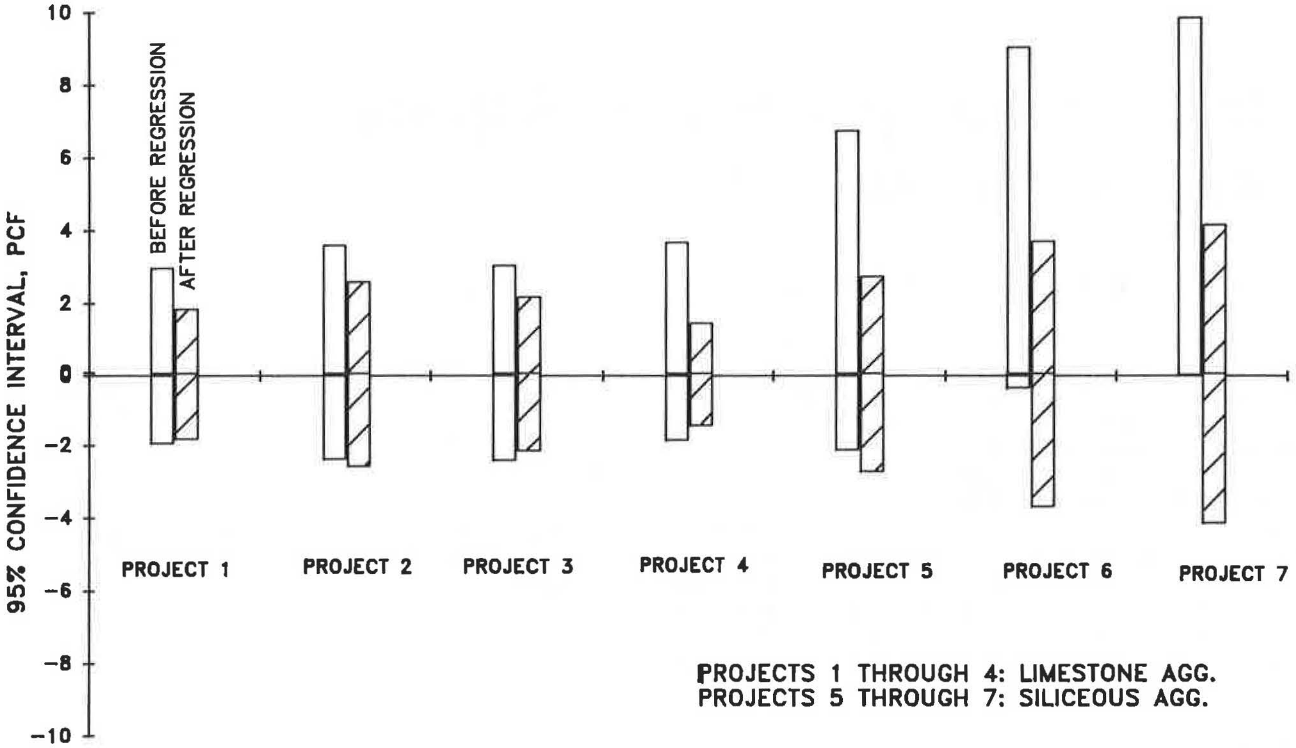

FIGURE 13 **Ninety-five-percent confidence intervals for differences between core and nuclear densities before and after regression for different projects.**

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